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In memoriam of Prof. Dr. Andrzej Henkiel

Jointing in the Dukla Nappe (Outer Carpathians, Poland): an attempt at palaeostress reconstruction

Leonard MASTELLA and Witold ZUCHIEWICZ

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The joint network in the portion of the Dukla Nappe studied originated in two stages showing different orientations of the stress field axes. The older, compressive stage I was characterised by a N45°E-orientated (at present coordinates) horizontal σ_1, and formation of the diagonal, shear (S_L and S_R) joint system. The younger, extensional stage II was characterised by vertical σ_1 and horizontal, N35°E-orientated (also at present coordinates) σ_3, suitable for formation of the fold-parallel joints. At the turn of the first stage, under diminishing horizontal compression (σ_1 trending N35°E), the cross-fold T joints developed. The orientation of the maximum compression axis changed between stages I and II. The first stage probably commenced while strata which were not fully lithified underwent shortening, and lasted until the termination of nappe emplacement. The second stage, in turn, is associated with post-orogenic collapse of the Carpathians, whose onset in the study region began at least in Late Miocene times.

Leonard Mastella, Institute of Geology, Warsaw University, Żwirki i Wigury 93, PL-02-089 Warszawa, Poland; Witold Zuchiewicz, Institute of Geological Sciences, Jagiellonian University, Oleandry 2A, PL-30-063 Kraków, Poland *(received: Juni 12, 2000; accepted: September 20, 2000).*

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INTRODUCTION

The objective of this paper is to describe and characterise the origin of jointing in the Polish segment of the Dukla Nappe (Fig. 1), as well as to show that joints in structurally complicated settings, such as the Dukla Nappe, are related to far-field stresses and that they can be used as key tools in palaeostress reconstructions. This study is a continuation of previous research, initiated in the Polish Outer Carpathians by Książkiewicz (1968), and in the Dukla Nappe by one of us in the late 1980s and early 1990s (Henkiel and Zuchiewicz, 1988; Zuchiewicz and Henkiel, 1995).

Some authors claim that jointing generally precedes faulting (Sheperd and Huntington, 1981; Segall and Pollard, 1983) and folding (*i.a.* Cook and Johnson, 1970; Tokarski, 1977), whereas others maintain that systematic jointing in fold-thrust belts post-dates the main orogenic compressional event (Meere and Rogers, 1999) and that it can rarely be used as a far-field stress indicator (*e.g.* Pollard and Aydin, 1988). Yet another group of geologists concludes that joints can be initiated before, during and after folding (Hancock, 1964, 1985; Rixon *et al.*, 1983). It has recently been suggested that joints in young fold-and-thrust belts are related to far-field stresses and that they can easily be used in palaeostress reconstructions (Mastella *et al.*, 1997; Świerczewska and Tokarski, 1998). The Dukla Nappe in the Outer Carpathians of Poland, showing fairly complicated structure, appears to be a perfect area to test this hypothesis.

We have chosen the Dukla Nappe as a test area, since this region has been studied extensively and has a good coverage of detailed geological maps (*i.a.* Wdowiarz, 1931; Ślączka, 1971, 1985; Tokarski, 1975*a*; Ślączka and Żytko, 1979; Koszarski, 1985; Kuśmierek, 1990).

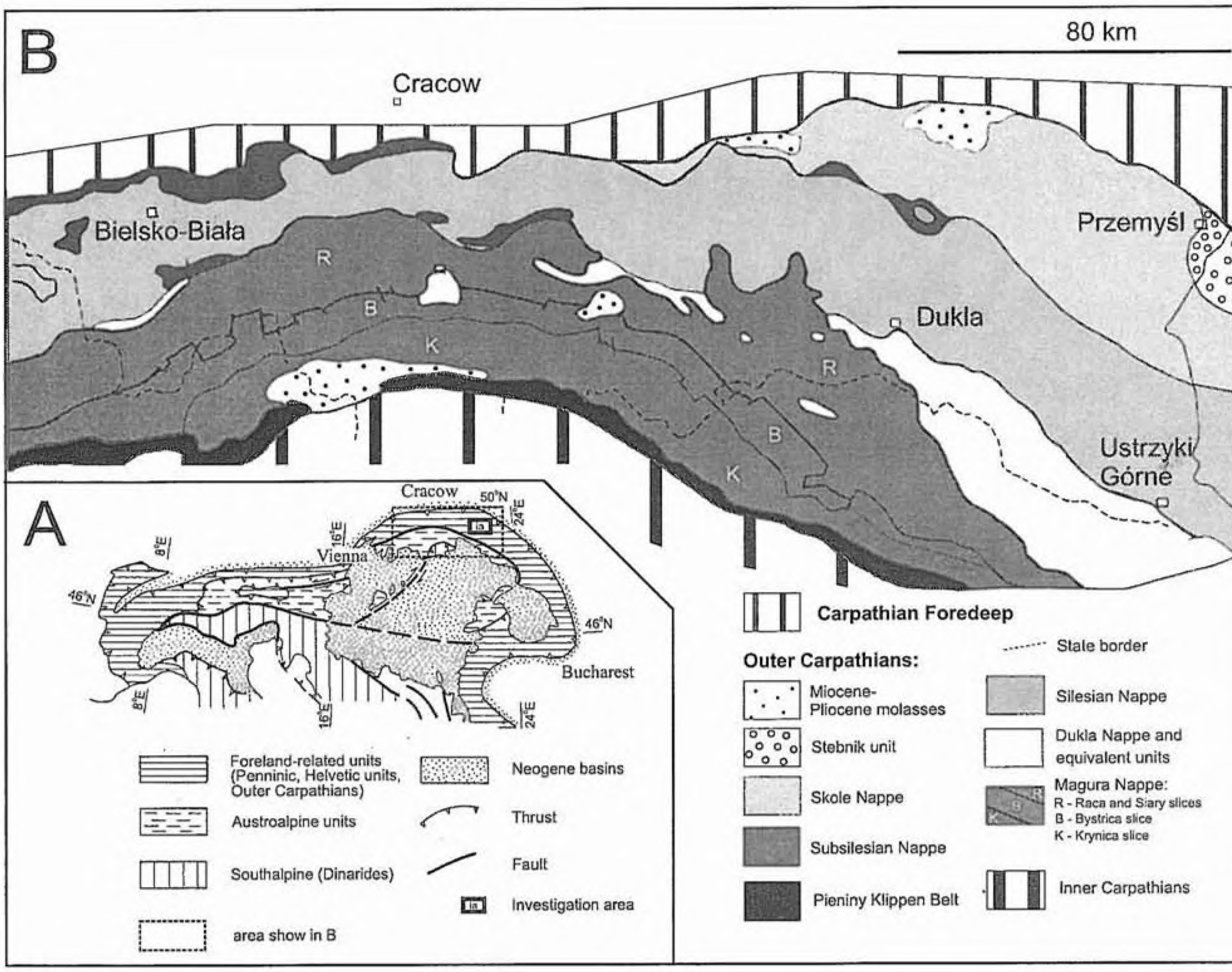


Fig. 1. A — Structural sketch of the Carpatho-Pannonian region (based on Neubauer *et al.*, 1997, modified); B — Tectonic sketch of the Polish Outer Carpathians (based on Żytko *et al.*, 1989)

Definition. The term "joint" is used here as a field term describing "... a barren, closed fracture on which there is no measurable slip or dilation at the scale of observation" (Hancock, 1985, p. 445; *cf.* also Dunne and Hancock, 1994). Only penetrative joints which are perpendicular to bedding, systematic, which cut singular beds and whose spacing is roughly equal to the thickness of the host bed, have been taken into account (Jaroszewski, 1972, 1980; Dunne and Hancock, 1994). Following the classification schemes by Engelder (1985) and Bahat (1998), we shall be dealing with tectonic and burial/syntectonic joints, respectively.

STATE OF RESEARCH

Joints are ubiquitous structures in the Cretaceous through Tertiary flysch strata of the Polish Outer Carpathians, and have been studied by numerous authors (*i.a.* Bober and Oszczypko, 1964; Książkiewicz, 1968; Tokarski, 1975*b*, 1977; Lenk, 1981; Aleksandrowski, 1985*a, b*, 1989; Mastella, 1988; Mardal, 1995; Zuchiewicz and Henkiel, 1995; Mastella *et al.*, 1997; Zuchiewicz, 1997*a, b*, 1998*a, b*; Tokarski and Świerczewska, 1998). The relation of jointing to regional fold trends has become easy to establish owing to recently published calculations of map-scale fold axes within homogeneous domains throughout nearly the whole of the Polish Outer Carpathians (Mastella *et al.*, 1997; Szczęsny, 1998).

Jointing in the Polish segment of the Dukla Nappe and the neighbouring portion of the Silesian Nappe has been dealt with by Henkiel and Zuchiewicz (1988), Zuchiewicz and Henkiel (1995), Rubinkiewicz (1996, 1998), and Zuchiewicz (1997*a*, 1998*a*). Interpretations contained in papers published before 1996, however, are biassed by the fact that the orientations of the measured joint sets has not been corrected for bedding and fold plunge attitudes. Such corrections were then difficult to apply due to the lack of necessary computer software.

GEOLOGICAL SETTING

The eastern portion of the Outer Carpathians comprises several nappes that are thrust over each other from the SSW to

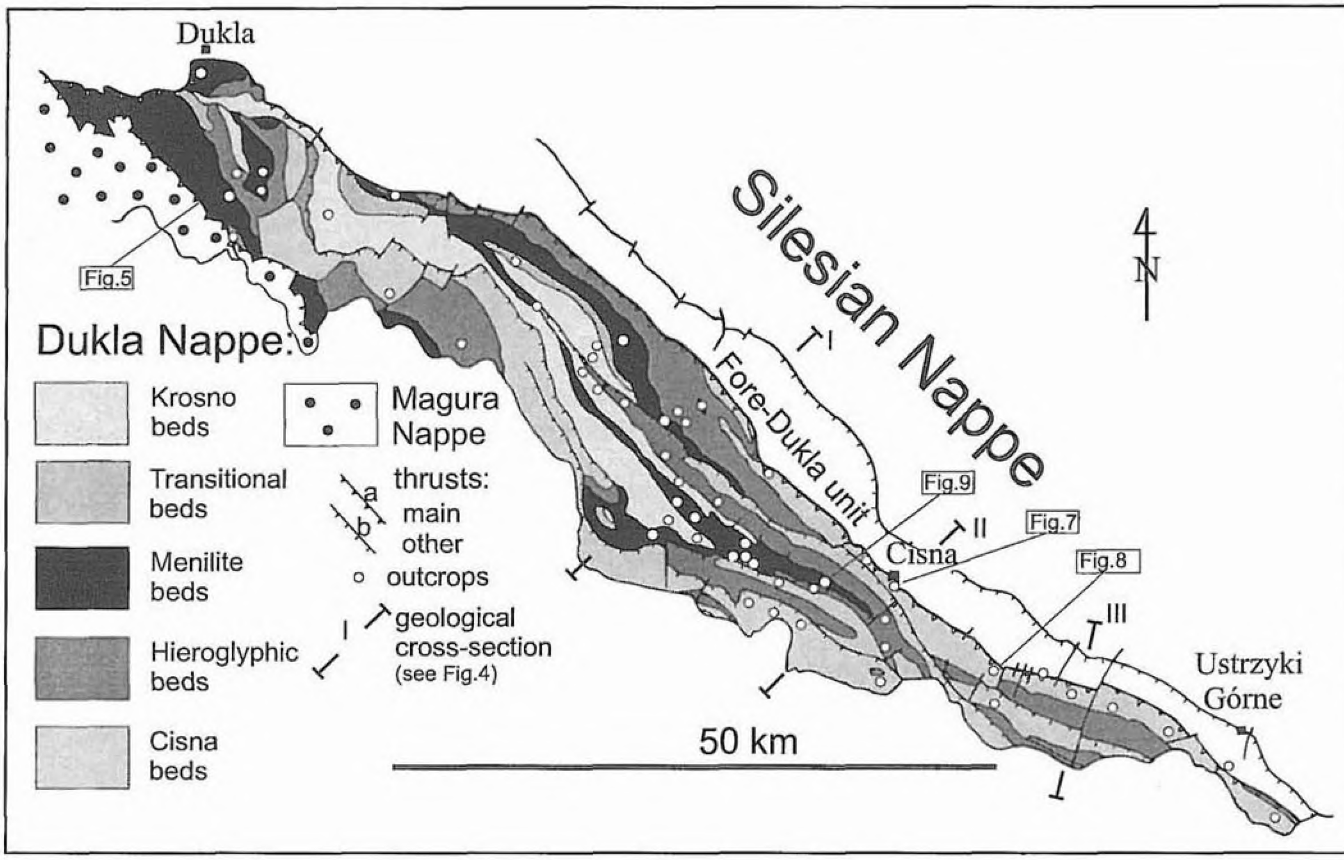


Fig. 2. Geological sketch of the Polish segment of the Dukla Nappe (based on Ślączka and Żytko, 1979)

the NNE (Fig. 1). The thrusting proceeded throughout middle and Late Miocene times, except for the inner part of the Magura Nappe where it had begun in the Paleogene (*cf.* Tokarski and Świerczewska, 1998; Żytko, 1999). The stratigraphic inventory of these nappes includes Cretaceous through Lower Miocene flysch strata of variable thicknesses (Książkiewicz, 1977; Oszczypko and Ślączka, 1989). Thin-bedded turbidites are strongly deformed by tight folds and are included in a number of imbricated thrust sheets, locally forming antiformal stacks, whereas thick-bedded turbidites are less deformed and are accreted in slightly imbricated thrust sheets (Roca *et al.*, 1995). The thrusting propagated gradually with time as a result of oblique convergence between the Eurasian Plate and Alcapa (*cf.* Royden, 1988; Oszczypko and Ślączka, 1989; Ellouz and Roca, 1994). Most of the shortening took place between the Late Oligocene and the end of the Sarmatian during an interval of 16–13 Ma (Roca *et al.*, 1995; Oszczypko, 1996).

The Dukla Nappe belongs to the Fore-Magura group of slices (Ślączka and Kaminski, 1998; and references therein) and is exposed at the surface in the eastern portion of the Polish Carpathians. To the south it is in contact with the strongly tectonised Jasło Nappe or the Magura Nappe, whereas towards the west it passes under the Magura Nappe into the Grybów unit which, in turn, is underlain by the Obidowa–Słopnice slice (Ślączka, 1971; Cieszkowski *et al.*, 1985; Ślączka and Kaminski, 1998). The Dukla Nappe itself usually rests on top of the Silesian Nappe, although locally other tectonic slices, such as the Fore-Dukla and Michalczowa units, composed of Cretaceous to Paleogene shallow-water successions, occur beneath the Dukla sole thrust (Cieszkowski, 1992; Roca *et al.*, 1995).

Lithostratigraphy. The Dukla Nappe is composed of folded Cretaceous to Paleogene deep-water flysch strata (Ślączka, 1971, 1985; Koszarski, 1985; see also Figs. 2, 3). The stratigraphic inventory includes a sequence of alternating incompetent and competent shales and medium- to thick-bedded turbidites, starting from the Senonian Łupków beds through to the Oligocene-Lower Miocene — Krosno beds, the latter oc-

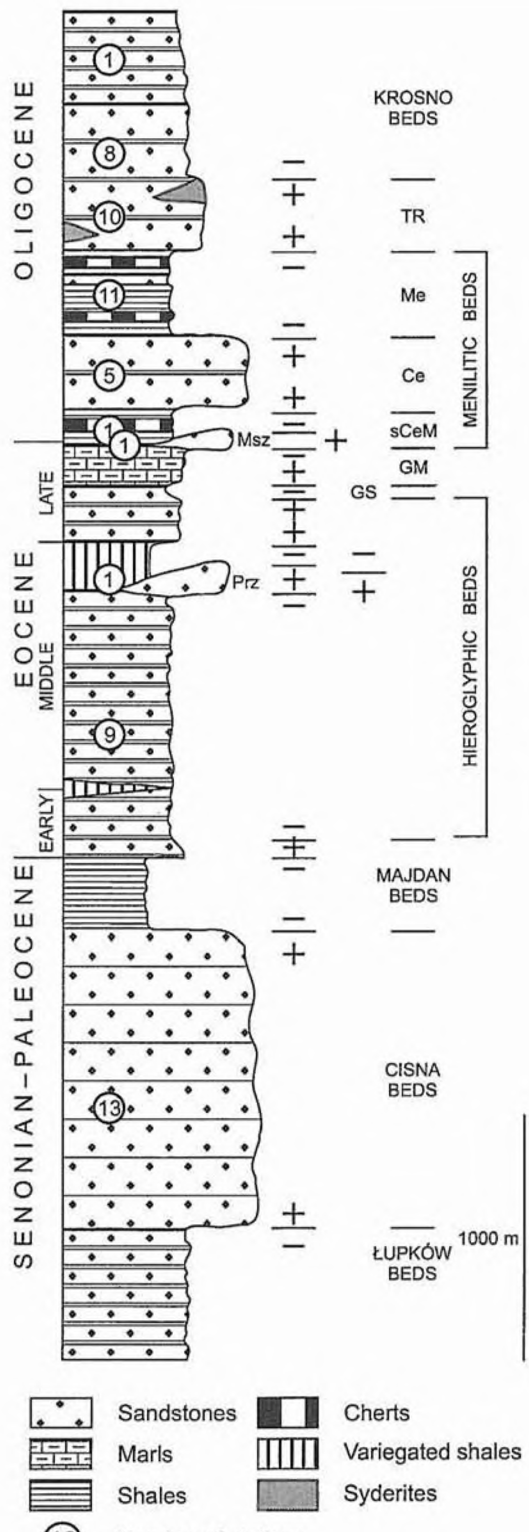


Fig. 3. Lithostratigraphic log of the Dukla Nappe (based on Ślączka and Żytko, 1979; Ślączka, 1985)

Prz — Przybyszów sandstones, GS — green shales, GM — Globigerina marls, sCeM — sub-Cergowa marls, Msz — Mszanka sandstones, Ce — Cergowa sandstones, Me — menilite shales, TR — transitional beds; + — competency, and – — incompetency of adjacent lithostratigraphic members

curring in marginal parts of the Dukla Nappe only (Fig. 2). The total thickness of the Dukla sedimentary sequence estimated from study of exposures and borehole data ranges between 4000 and 5700 m (Ślączka and Żytko, 1979; Gucik *et al.*, 1980). The most resistant lithostratigraphic members are represented by thick-bedded sandstones of the Cisna (Upper Cretaceous-Paleocene) and Cergowa sandstones (Oligocene) (Fig. 3).

Tectonics. The Dukla Nappe comprises a number of NNW–SSE to NW–SE and WNW–ESE striking, imbricated folds (Figs. 2, 4) which plunge towards the north-west below the Magura or Jasło Nappes (Ślączka and Żytko, 1979; Ślączka and Kaminski, 1998). The unit is separated from the Silesian Nappe by a thrust plane which in the eastern part is locally overturned (Ślączka and Żytko, 1979; Ślączka, 1985; Rubinkiewicz, 1996). The minimum amount of thrusting of the Dukla Nappe upon the Silesian Nappe has been found to attain 15 km south of Wetlina (Cieszkowski *et al.*, 1985).

According to Ślączka (1971, 1985), the Dukla Nappe is subdivided into two subunits, the internal and external ones, separated by a low-angle thrust (Fig. 4). The external subunit is composed of several steeply dipping horses, the internal one showing nearly flat bedding. The lack of the Krosno beds in the internal subunit is thought to indicate earlier uplift in this domain (Ślączka, 1971, 1985). Folded strata of the Dukla Nappe are cut by NNE- to NE-orientated, mostly strike-slip faults, showing both sinistral and dextral components of motion.

The Dukla Nappe with the coeval Grybów, Obidowa–Słopnice and Michalczowa slices were emplaced during the Early Miocene (Ślączka, 1985; Cieszkowski, 1992). The final emplacement of the nappe possibly post-dates the folding of flysch strata, as the Dukla sole thrust cuts both most of the Dukla folds and those of the underlying Silesian Nappe (Roca *et al.*, 1995). Folding in the Dukla Nappe was restricted, most probably, to Late Oligocene times and was post-dated by an episode of strike-slip and, during post-orogenic collapse, normal faulting (Książkiewicz, 1977; Ślączka and Kaminski, 1998). Recently published pilot studies made at one locality in the NW portion of the Dukla Nappe and at a number of stations located in the Silesian and Magura Nappes (Decker *et al.*, 1999) appear to indicate two episodes of thrusting, namely the Paleogene-Early Miocene N-directed in-sequence thrust shortening, and an Early-Middle Miocene NE-directed out-of-sequence episode, followed by post-Middle Miocene dextral strike-slip event. The inferred timing of these events is, however, poorly constrained.

MATERIAL AND METHODS

We have analysed joint patterns at 60 stations, individual singular large exposures or groups of exposures, spread unevenly throughout the Polish segment of the Dukla Nappe. The stations studied represent Senonian-Paleocene (22%), Eocene (17%) and Oligocene (*ca.* 62%) strata (*cf.* Fig. 3), most of the data coming from medium- to thin-bedded (47%) and thick-bedded (33%) flysch sequences. We have measured the attitude of bedding and joint surfaces, as well as the orientation of small-scale structures associated with joints, including: *en*

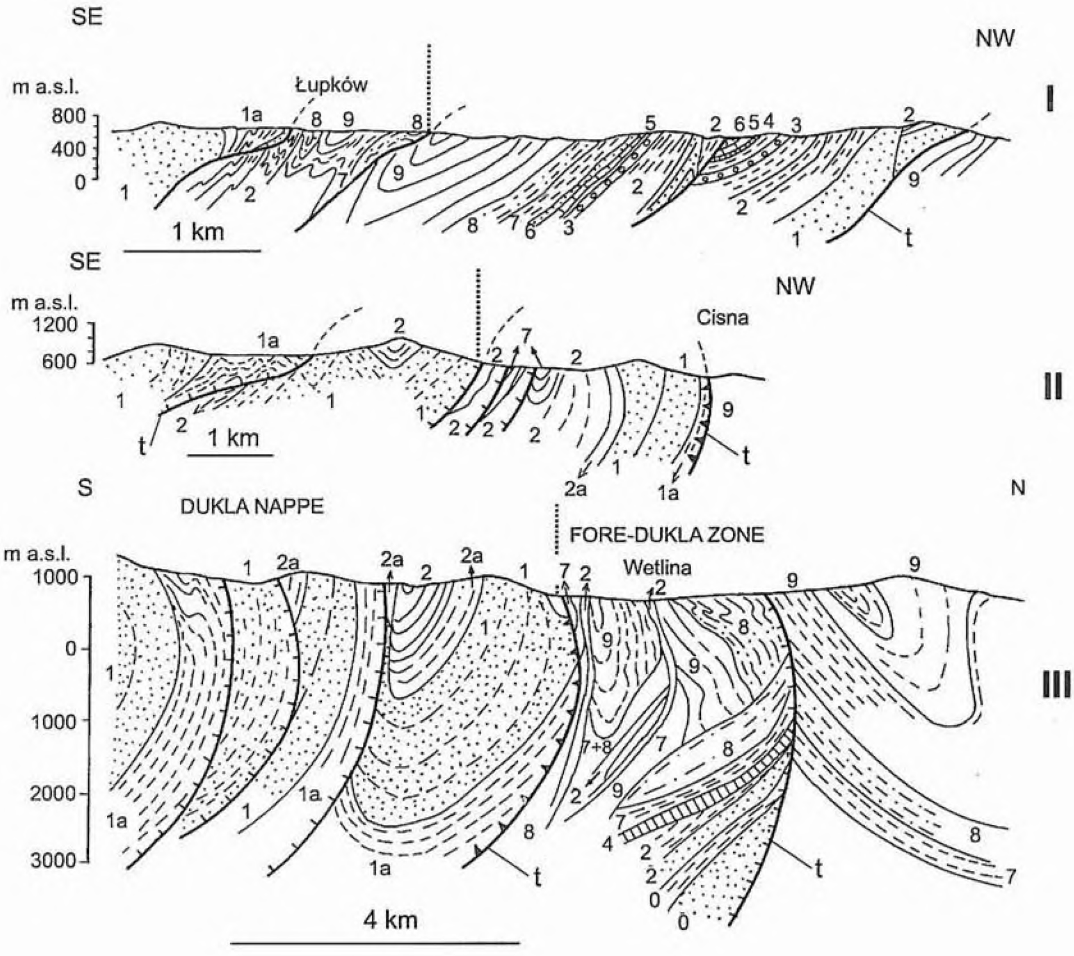


Fig. 4. Simplified geological cross-sections through the Dukla Nappe (based on Ślączka, 1971, 1985)

0 — Istebna beds, 1 — Cisna beds, 1a — Łupków beds, 2 — hieroglyphic beds, 2a — Majdan beds, 3 — Przybyszów sandstones, 4 — Mszanka sandstones, 5 — sub-Cergowa marls, 6 — Cergowa sandstones, 7 — menilite beds, 8 — transitional beds, 9 — Krosno beds, t — different order thrusts

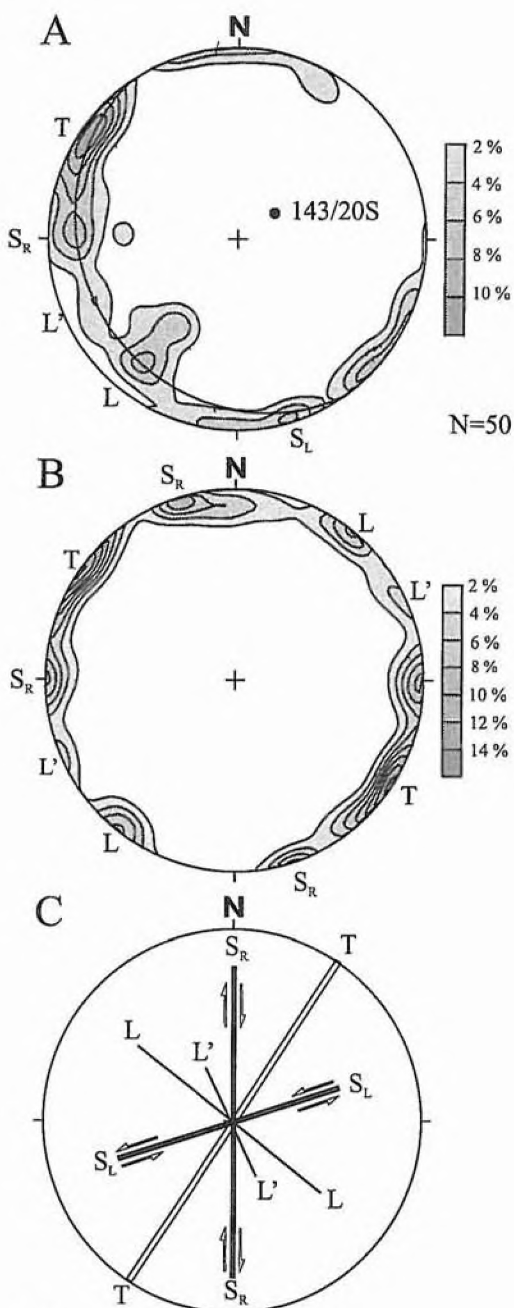
echelon fractures, feather fractures, and tectonic fringes. At each station 50 to 120 joint surfaces have been measured, a figure statistically representative for the region (Mastella, 1988; Zuchiewicz, 1997*a*; Rubinkiewicz, 1998). Measurement resolution was ±2°. The data have been plotted on lower hemisphere Schmidt projections and then bedding- and fold plunge-corrected, using the STEREONET program.

Following Price (1959, 1966), Książkiewicz (1968), and Jaroszewski (1972), we accept a prefolding — at incipient stage — origin of the majority of joint sets. This is indicated by the fact that joints belonging to a single set and showing variable orientation in fold limbs, attain the same orientation after rotating fold limbs into horizontal position about the bedding strike. Moreover, observations carried out in other parts of the Outer Carpathians indicate that some of the joints which were formed in poorly lithified strata (Tokarski, 1975*b*; Mastella, 1988; Mastella *et al.*, 1997; Świerczewska and Tokarski, 1998), are displaced by fold slip (Mastella and Ozimkowski, 1979) and form tectonic ledges (*cf.* Jaroszewski, 1968) at intersections with bedding planes (Mastella, 1988).

Therefore, apart from standard statistical procedures (Fig. 5A), we have also studied the joint pattern after bedding correction, following the suggestions of Murray (1967) and Książkiewicz (1968). As a result, we have obtained considerable unification of orientations of individual joint sets (Fig. 5B, C) that enabled further calculations (Fig. 5D).

JOINTING — DESCRIPTION

The regional joint network comprises five sets (Fig. 6). At individual exposures, however, usually two to four sets can be encountered (Figs. 7–9). The sets maintain a relatively stable orientation in respect to the strike of map-scale folds. Sets



D

Azimuth				
S_R	S_L	σ_1	T	2Θ
2	74	38	34	72

Fig. 5. Technique of determining joint pattern parameters, exemplified by statistical processing of data measured at stations located on the Panna stream (*cf.* Fig. 2; thin-bedded sandstones, menilite beds)

A — stereogram of joints before bedding correction, lower hemisphere Schmidt net; **B** — the same stereogram after bedding correction; **C** — interpretative diagram showing position of main joint sets; arrows portray tendency to strike-slip motion; **D** — selected parameters of the joint network; N — number of data; cross-fold: T — transversal, S_R — diagonal dextral, S_L — diagonal sinistral; L and L' — fold-parallel; great circle (bedding plane) and dot (normal to bedding plane) mark the attitude of bedding

showing the same regional orientation display both similar surficial features and the type of intersection with bedding surfaces.

Cross-fold joints comprise a single set (T; Figs. 6, 9) striking perpendicular or sub-perpendicular to map-scale fold axes (80–90°), and two diagonal sets (S_R, S_L) striking at high angles (60–80°) to these axes (Figs. 6, 7A, 8). The acute bisector between these two sets is orientated perpendicular to map-scale folds. Fold-parallel joints (L) (Figs. 6–9), (L') (Figs. 6, 7A) strike parallel or at small angles to map-scale fold axes and are perpendicular or subperpendicular to bedding (70–90°).

CROSS-FOLD JOINTS

The diagonal system comprises set S_R orientated N4°W–N25°E, clustering between N6°–15°E, and set S_L orientated, respectively, N56°–85°E and N75°E (Fig. 10). Some of the S_R joints terminate on the S_L joints and *vice versa*. No regional variability of joint set orientation has been found. Both sets, although orientated differently at individual exposures, intersect one another at an acute angle of 60–75° (Figs. 5, 7A, 8), whose bisector strikes SW–NE throughout the study area. This property points to a conjugate character of these two sets.

Joints of the two sets are morphologically similar. Fissures associated with both the sets, a few millimetres wide, are filled in places by calcite. Both surfaces of a singular, non-mineralised joint resemble a form-cast coupling or are accompanied by plumose structures of axes parallel to the joint/bedding surface intersection. Acute terminations of plumose structures are, even on surfaces belonging to the same joint set, variably orientated, pointing to a differently directed sense of initial propagation of joints (Parker, 1942). The presence of such structures appears to indicate an extensional mode of joint opening (Bankwitz, 1965, 1966; Engelder, 1985).

The surfaces of S_R and S_L joints are planar and their traces on bedding surfaces are usually rectilinear (Figs. 7A, 8). Numerous joints of the S_R and S_L sets are accompanied by minor feather fractures, striking at 30° versus the joint surface (Figs.

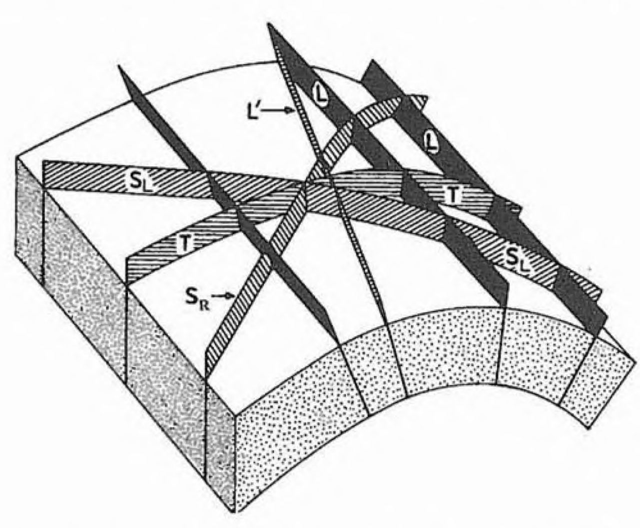


Fig. 6. Joint pattern in a sandstone bed (based on Książkiewicz, 1968, modified)

For explanations see Fig. 5

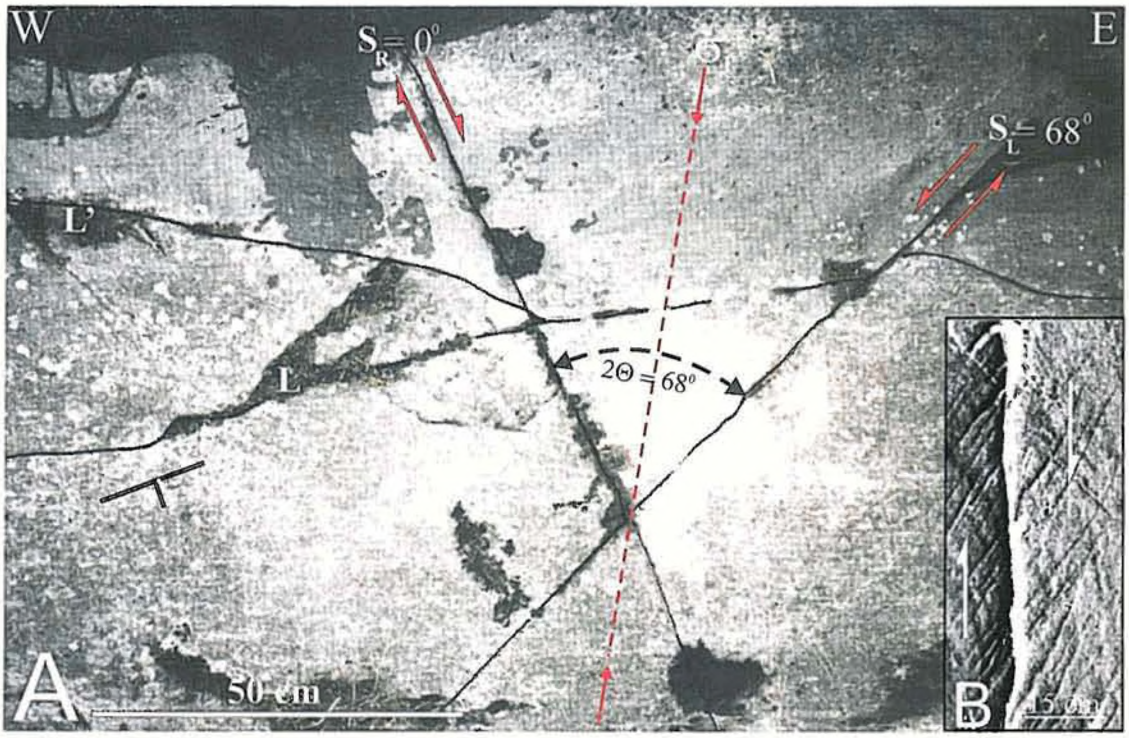


Fig. 7. A — Joints on top of a thick sandstone bed, Cisna beds (station no. 58, Solinka stream, 2 km south of Cisna); dashed line marks the acute bisector between conjugate shear joints (σ_1); B — Close-up of feather fractures associated with set S_R

For other explanations see Fig. 5

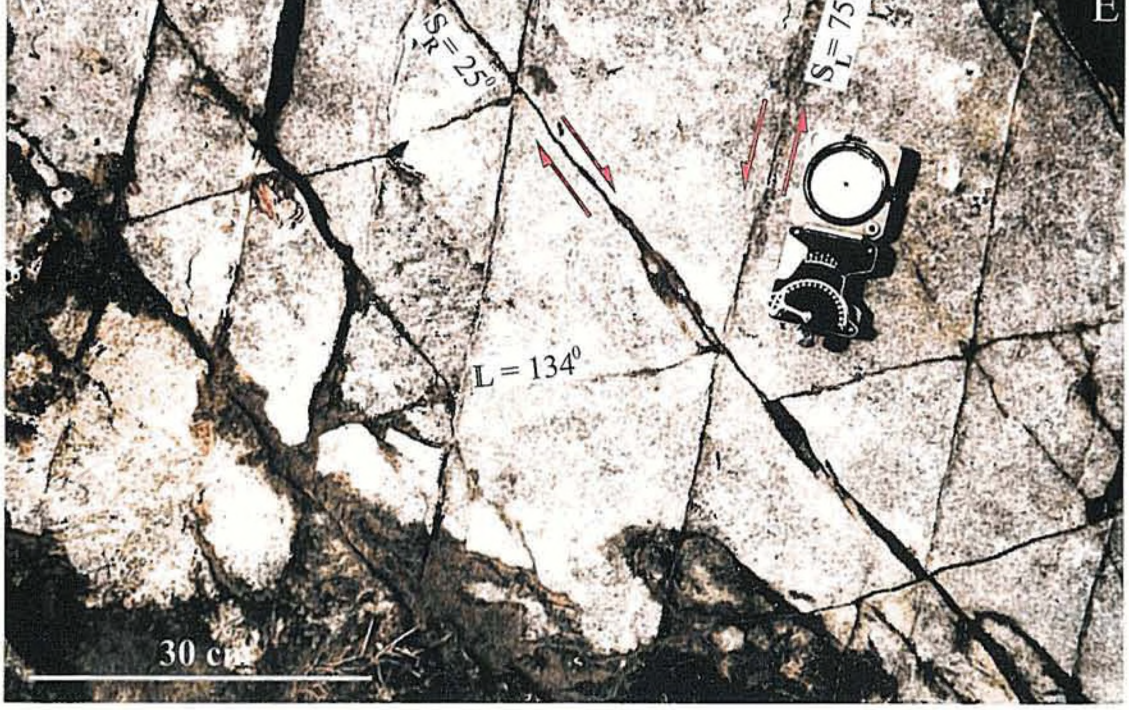


Fig. 8. Joint pattern in a thick Cisna sandstone beds (Wetlinka stream)

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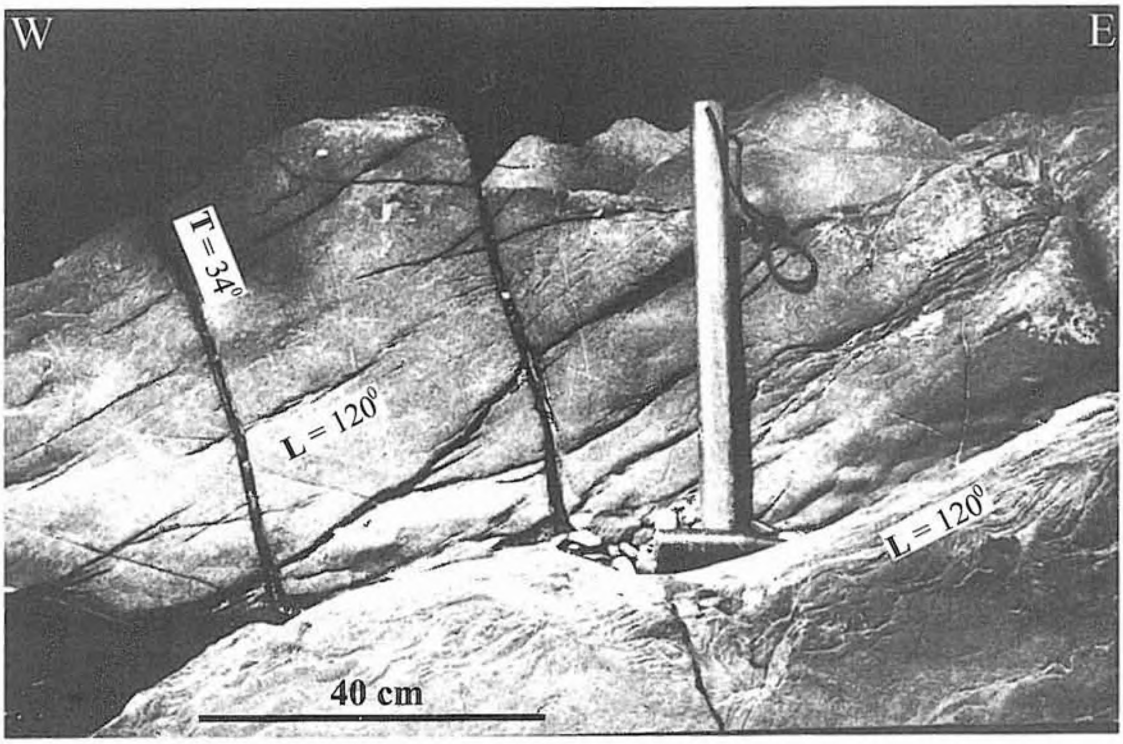

Fig. 9. Joints in silicified, medium-bedded sandstones of the menilite beds (station no. 44, Solinka stream south of Żubracze village)

For explanations see Fig. 5

7B, 8), that represent low-angle Riedel shears (*sensu* Riedel, 1929; Bartlett *et al.*, 1981). Locally, instead of a linear trace, an *en echelon* array composed of low-angle Riedel shears can be encountered, passing sometimes into a continuous joint surface. Such shears are probably incipient forms preceding the formation of continuous diagonal joints. Riedel shears penetrate only a few millimetres into the host bed. Joints opened along *en echelon* arrays of shear fractures bear fringe structures on their surfaces. Some of the *en echelon* cracks are filled by material derived from country rocks or by calcite contaminated by this material.

The strike of T joints varies along the segment of the Dukla Nappe studied from N24°E to N46°E, clustering at N35°E (Fig. 11A). The surfaces of T joints are not planar, and their traces on bedding surfaces are usually curvilinear. The T joints are not accompanied by feather and *en echelon* fractures, and are lined by mineral (usually calcite) veins less frequently in comparison to the S_R and S_L diagonal joints. Joint surfaces are usually devoid of fringe structures. Fissures associated with this set are commonly open, unlike those related to the diagonal sets. The T joints are, in turn, frequently accompanied by plumose and pinnate structures that do not show any preferred orientation.

Fold-parallel (longitudinal) joints (L, L') strike sub-parallel to the map-scale folds and comprise two sets of different orientation (Figs. 5, 7–9, 12). Joints of set L are usually parallel to map-scale fold axes, whereas joints of set L' strike at low angles (up to 20°) to these axes.

The most frequent joints of set L strike N100°–130°E, clustering at N125°E (Fig. 12), and are nearly always parallel to the bedding strike. Joints of set L', in turn, strike N145°–155°E (Fig. 12) and are usually independent of map-scale fold orientation.

Both joint surfaces and traces of their intersection with bedding planes are similar in the two sets. Traces of intersection with bedding planes are discontinuous or fading, sometimes curvilinear (Fig. 7A). Surfaces of a single joint are usually of the "form-cast" type. Plumose structures are particularly abundant upon most of the L' joint surfaces, and very rare on L joints. This is particularly visible in large fold hinges where such joints resemble textbook examples of radial fractures (Jaroszewski, 1980; Price and Cosgrove, 1994). It is important to note that the origin of fold-parallel joints in the Outer Carpathians has not been dealt with except in preliminary comments by Książkiewicz (1968) and Aleksandrowski (1989), mostly regarding the Magura Nappe. This description is a yet preliminary attempt to assess the importance of these joint sets in the Dukla Nappe.

JOINTING — INTERPRETATION

Cross-fold joints. Morphological properties of the diagonal (S_R, S_L) joints indicate that the incipient stage of their development was by shear, whereas their further opening proceeded in extensional mode (Price, 1959, 1966; Książkiewicz, 1968; Jaroszewski, 1972; Engelder, 1985). The pattern of *en echelon* arranged gashes and feather fractures shows that the S_R and S_L sets represent, respectively, dextral and sinistral shears (Figs. 5, 7, 8), whose acute bisector is orientated SW–NE throughout the Dukla Nappe. Furthermore, abutting relationships suggest that the S_R and S_L joints are roughly coeval and were formed as "potential shear surfaces" in a triaxial stress field (Mandl, 1988; Engelder, 1989; Dadlez and Jaroszewski, 1994), and that the acute dihedral angle comprised between these sets represents a double value of the angle of shear, 2Θ (Fig. 7A). The occurrence of plumose structures, in turn, points to subsequent extensional opening of these joints (Mastella, 1988).

We suppose, following also our previous study (*cf.* Mastella *et al.*, 1997), that these joints are shear fractures (Hancock, 1985) that form a conjugate system. Moreover, some of the joints were formed when the host strata were poorly lithified, as indicated by contamination of mineral veins that fill the joints by material derived from the host strata (Mastella, 1988).

Analysis of the angle of shear. The acute angle comprised between the S_R and S_L sets (double value of the angle of shear, 2Θ) changes at individual exposures from 50 (Fig. 8) to 72° (Fig. 5D). Nearly 80% of our data, however, fall into an interval of 60–70° (Figs. 13, 14), typical for conjugate joint sets (Handin *et al.*, 1963; Hancock, 1985). There is a regional tendency towards the increase of 2Θ from the west (60°) the east (70°). This tendency is not tectonically-induced, but it is rather controlled by lithological properties of the host rocks (*cf.* Mandl, 1988). In the eastern part, most measurements have been made in poorly lithified sandstones of the Cisna beds, as well as in mudstones of the transitional beds, both showing much lower values of cohesion and internal friction as compared, for instance, to those of siliceous sandstones of the hieroglyphic or menilite beds. Therefore, the angle of shear in the Cisna and transitional beds attains higher values than that in the hieroglyphic and menilite beds (Fig. 14).

The morphology of T joints indicates that their development proceeded without the initial "shear" stage and that they are extension (mode I) fractures (Bankwitz, 1965, 1966; Książkiewicz, 1968; Engelder, 1985; Price and Cosgrove, 1994).

Fold-parallel joints. Both the L and L' sets are devoid of properties that would point to their shear origin. The morphology of joint surfaces, occurrence of plumose structures (particularly common in the L' set), and characteristic discontinuous

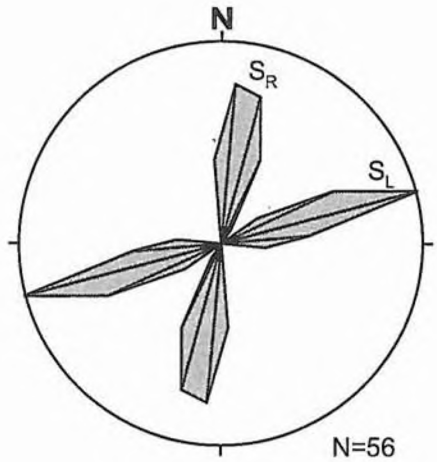

Fig. 10. Histogram showing the distribution of S_R and S_L joint sets in the portion of the Dukla Nappe studied

For other explanations see Fig. 5

or fading, in places nonlinear, traces of intersection with bedding planes appear to indicate a tensional origin of joints of the L set and of those L' joints which are parallel to the bedding strike (Książkiewicz, 1968; Aleksandrowski, 1989).

Taking into account the tensional character of all L and some of L' joints, as well as their association with hinge zones of folds one can hypothesize, following Aleksandrowski (1989), that these joints originated during early stages of folding.

DISCUSSION

The review above leads us to conclude a differentiated origin of individual sets and systems of the regional joint network, formed in different stress fields and at different times. The type and orientation of these fields can be reconstructed from the properties of joints (Książkiewicz, 1968; Jaroszewski, 1972; Aleksandrowski, 1985*a*, *b*, 1989; Zuchiewicz 1997*a*, *b*; Mastella *et al.*, 1997).

Stages of joint development. The onset of jointing should be related to a period when flysch strata of the Outer Carpathians were lithified enough to accumulate stresses resulting from regional compression induced by subduction of the Eurasian Plate under Alcapa (*i.a.* Pescatore and Ślączka, 1984; Oszczypko and Żytko, 1987; Tomek and Hall, 1993; Zoetemeijer *et al.*, 1999; and references therein). A triaxial stress field with horizontal, NE–SW orientated σ_1 (Tapponnier, 1977; Tokarski *et al.*, 1999) and vertical σ_2 dominated at that time, leading to initiation of the shear joint system within horizontal strata. Only locally, when the shear stress strength of host rocks was attained, S_R and S_L sets of this system could have been formed.

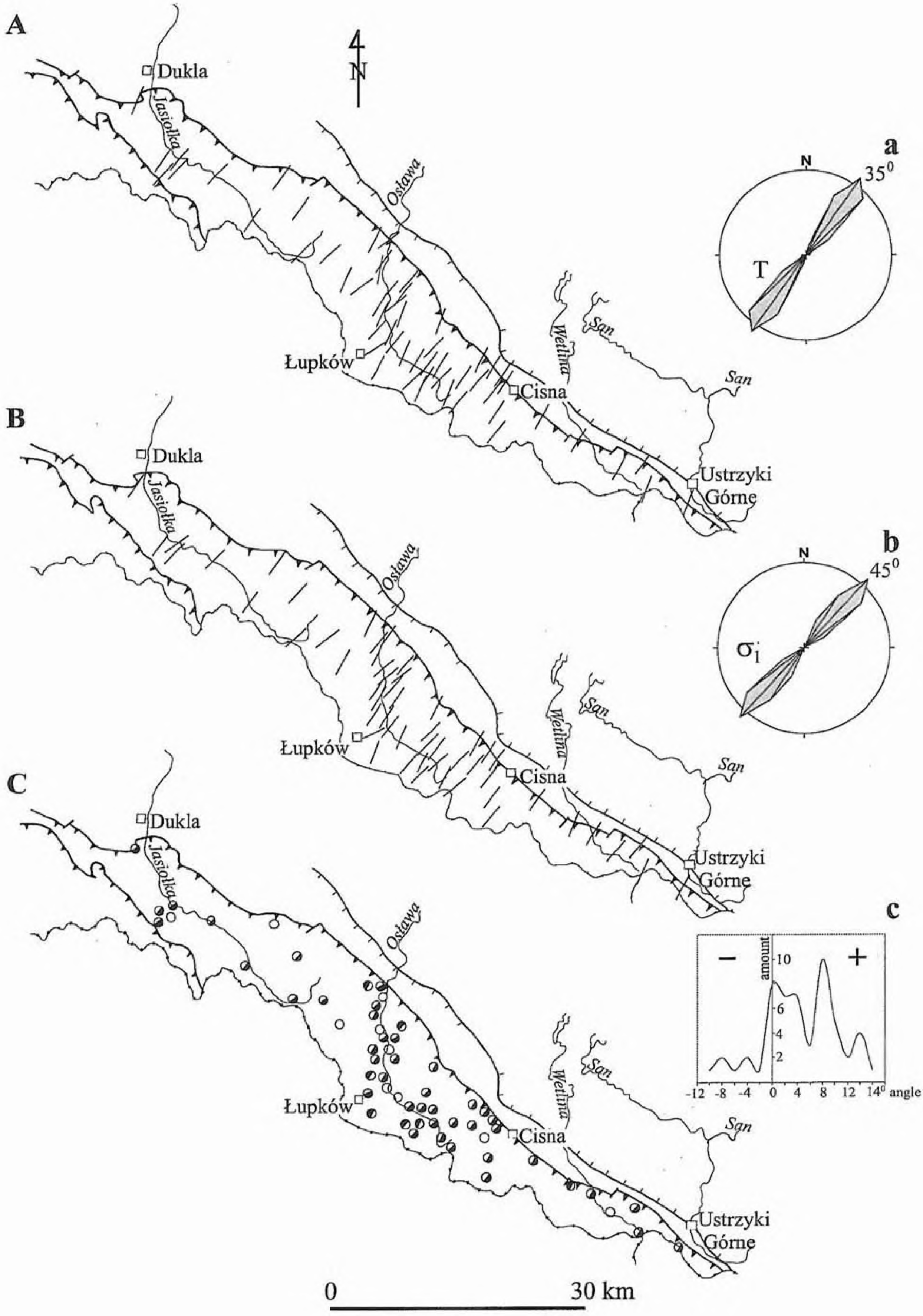

Fig. 11. Maps and histograms showing the spatial distribution of T (**A**, **a**), σ_1 (**B**, **b**), and amount of rotation of σ_1 versus T (**C**, **c**); black left-circle and – — anticlockwise, black right-circle and + — clockwise, white circles — T parallel σ_1

Folding commenced following the increasing NE–SW horizontal compressional stress. In broad hinges of large-scale open folds, tensional joints of set L, parallel to fold axes, started to develop. At the same time, with gradual steepening of folded strata, the S_R and S_L sets became open.

These processes lasted throughout the shortening of the Outer Carpathians until the beginning of post-orogenic collapse when, under diminishing horizontal compression (σ_1), perpendicular to it and also horizontal σ_3 axis attained a negative value. This change led to formation of extensional joints of set T. Later on, according to the Price's (1959) model, the remaining extensional L joints (perpendicular to T) developed, being locally post-dated by the youngest L' joints.

Our observations of recently opening joints in rocky river beds, undermined valley sides or quarries indicate that they are frequently predisposed by directions of stress relaxation in host rock massifs (*cf.* also Boretti-Onyszkiewicz, 1968).

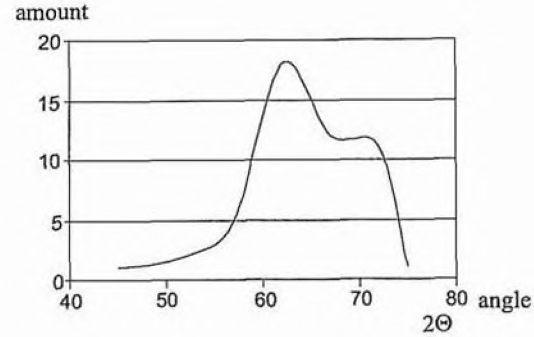

Fig. 13. Histogram showing the distribution of 2Θ values in the studied portion of the Dukla Nappe

ATTEMPT AT PALAEOSTRESS RECONSTRUCTION

Diagonal system. The oldest, diagonal joint system was initiated within subhorizontal strata in a shear triaxial stress field, characterised by positive axes of $\sigma_1 > \sigma_2 > \sigma_3$. The orientation of this field was reconstructed after bedding correction (Fig. 5B, C), by placing σ_1 along the acute bisector of 2Θ (Bucher, 1920, 1921; Ramsay and Huber, 1987; see also Figs. 5D, 7A). σ_1 strikes at individual exposures between N25°E and N62°E (Fig. 14), although nearly 60% of data fall within the limit of N34°–52°E, clustering at N45°E (Fig. 11B, b).

Orthogonal system. This system is younger than the diagonal one. Its older set T originated in the $\sigma_1 > \sigma_2 > -\sigma_3$ stress field, the axes σ_1 and $-\sigma_3$ being horizontal. The orientation of such joints is parallel to σ_1 (Price, 1959; Mastella and Szynkaruk, 1998). At the incipient stage of development of the orthogonal system, the axis σ_1 was orientated N35°±10°E (Fig. 11A, a), and joints T opened due to extension (σ_3) aligned roughly N125°E.

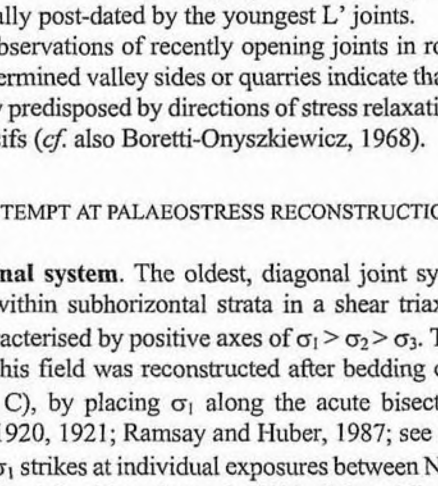

Fig. 12. Summary rose diagrams showing the frequency of occurrence of fold-parallel L and L' joint sets, as well as the strike of bedding measured at individual stations
N — number of data

Collapse-related extension parallel to the structural grain of that portion of the Carpathian belt induced a profound change in orientation of the stress field: σ_2 axis became horizontal and parallel to the axis of collapse, σ_1 attained a vertical attitude and its former orientation (N35°E horizontal; at present coordinates) was taken over by σ_3. In such a stress field most of extensional joints of set L originated. Joints belonging to the L' set were formed in a field of similar configuration of principal stress axes, although orientated differently, probably due to a local change of the collapse-related extension.

It is important to note that the orientation of σ_1 reconstructed for both shear joints and T joints is independent of the age of host strata (Fig. 14). This suggests that, since the onset of diagenesis of the Cisna beds, the shear joint-related stress field has maintained a constant orientation, similar to the stress field in which T joints developed (*cf.* also Rubinkiewicz, 1998). At present, in turn, a marked right-lateral rotation by *ca.* 10° of shear joint-related σ_1 (Fig. 11B, b) in respect to that of T joints (Fig. 11A, a), is notable (Fig. 11C, c). This tendency applies to both individual lithostratigraphic members (Fig. 14), and individual exposures (Fig. 11C). Since shear joints and T joints are not coeval, we suppose that they originated under differently-orientated stress fields.

Summing up, the joint network in the studied portion of the Dukla Nappe originated in two stages showing different orientations of the stress field axes. The older, compressive stage I was characterised by N45°E-orientated (at present coordinates) horizontal σ_1, and formation of the diagonal, shear joint system. The younger, extensional stage II was characterised by vertical σ_1 and horizontal, N35°E-orientated σ_3, suitable for formation of the fold-parallel L joints. At the turn of the first stage, under diminishing horizontal compression (σ_1 trending N35°E), the

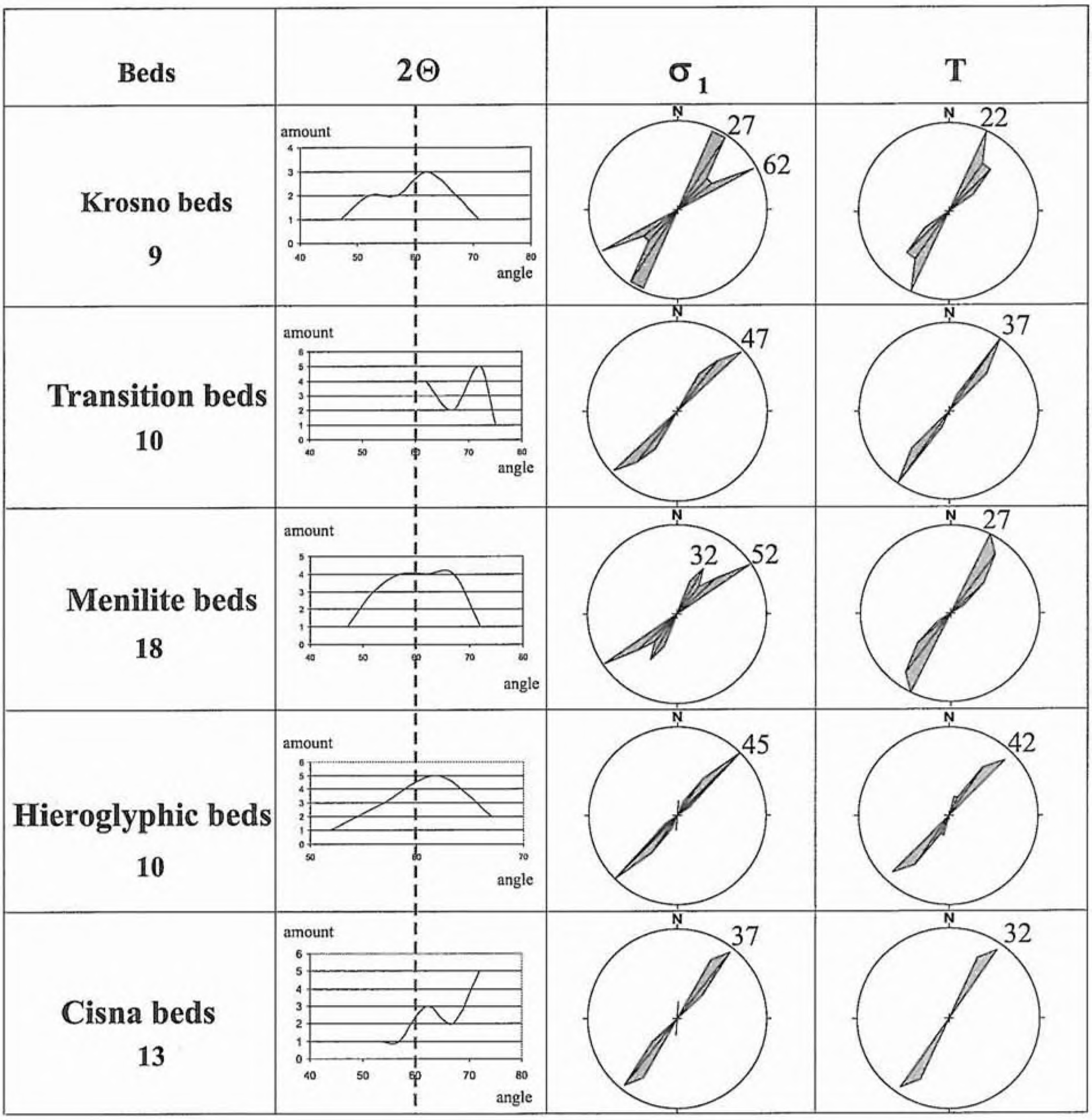

Fig. 14. Simplified lithostratigraphic log of the Dukla Nappe showing variability of the reconstructed values of 2Θ (angle of shear), σ_1 (principal stress axis), and T (cross-fold extensional joints)

9, 10, 18, 10, 13 — number of stations; for other explanations see Fig. 3

cross-fold T joints developed. The orientation of the maximum compression axis changed between stages I and II. Such changes have been described from a number of regions (*cf.* Angelier, 1994), and also from the Carpathians (Nemčok, 1993; Nemčok *et al.*, 1998; Zweigel, 1998).

The first stage probably commenced when strata which were not fully lithified underwent shortening, and lasted until the termination of nappe emplacement. The second stage, in turn, is associated with post-orogenic collapse of the Carpathians, whose onset in the study region began at least in Late Miocene times (Henkiel, 1977; Oszczypko, 1996; Ślączka and Kaminski, 1998; Decker *et al.*, 1999; Żytko, 1999; and references therein).

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